VISHNU – a dynamical evolution model for heavy-ion collisions*

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Work done in collaboration with

S.A. Bass, T. Hirano, P. Huovinen, Zhi Qiu, Chun Shen, and H. Song

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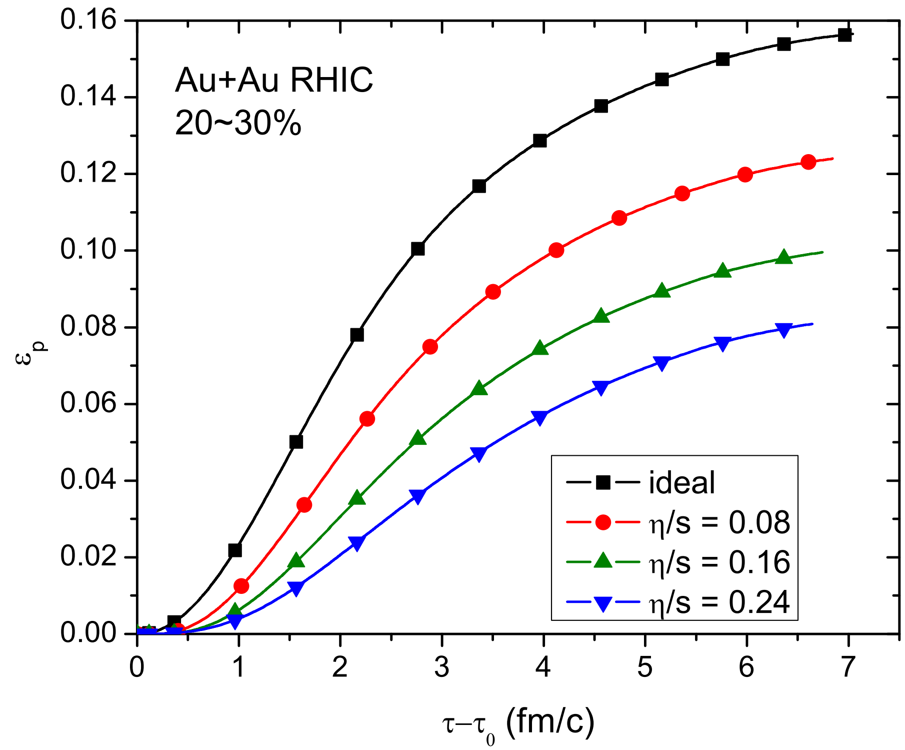
Prologue: How to measure $(\eta/s)_{\mathrm{QGP}}$

Hydrodynamics converts
spatial deformation of initial state $\Longrightarrow$
momentum anisotropy of final state,
through anisotropic pressure gradients



Shear viscosity degrades conversion efficiency

$$\varepsilon_x = \frac{\langle\langle y^2-x^2\rangle\rangle}{\langle\langle y^2+x^2\rangle\rangle} \Longrightarrow \varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle}$$

of the fluid; the suppression of ε_p is monotonically related to η/s.

The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow v_2^{ch}**:

$$\varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle} \Longleftrightarrow \frac{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \cos(2\phi_p)\, \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \frac{dN_i}{dy p_T dp_T d\phi_p}} \Longleftrightarrow v_2^{\mathrm{ch}}$$

Prologue: How to measure $(\eta/s)_{\mathrm{QGP}}$ (ctd.)

- **If** ε_p **saturates** before hadronization (e.g. in PbPb@LHC (?))

$\Rightarrow$ $v_2^{\mathrm{ch}} \approx$ not affected by details of hadronic rescattering below T_c

but: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dy d^2p_T}$ change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)

$\Rightarrow$ $v_2(p_T)$ of a single particle species **not** a good starting point for extracting η/s

- **If** ε_p **does not saturate** before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of ε_p over hadronic species and in p_T, but even the final value of ε_p itself (from which we want to get η/s)

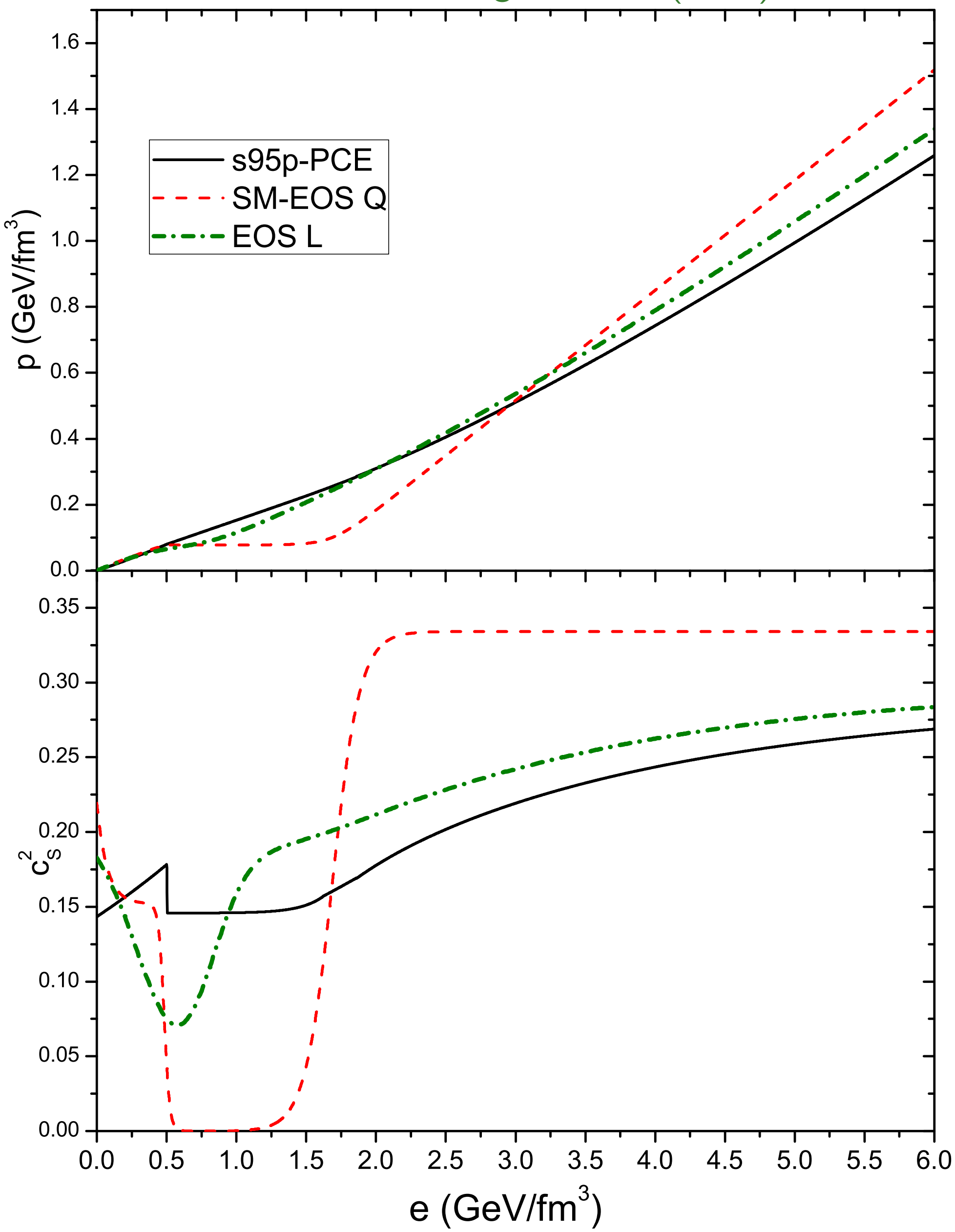
$\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

$\Rightarrow$ **VISHNU** ("Viscous Israel-Steward Hydrodynamics 'n' UrQMD")

(Song, Bass, Heinz, PRC83 (2011) 024912)   Note: this paper shows that UrQMD $\neq$ viscous hydro!

s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



High T: Lattice QCD (latest hotQCD results)

Low T: Chemically frozen HRG ($T_{\rm chem} = 165\,$MeV)

No softest point!

s95p-PCE: A realistic, lattice-QCD-based EOS

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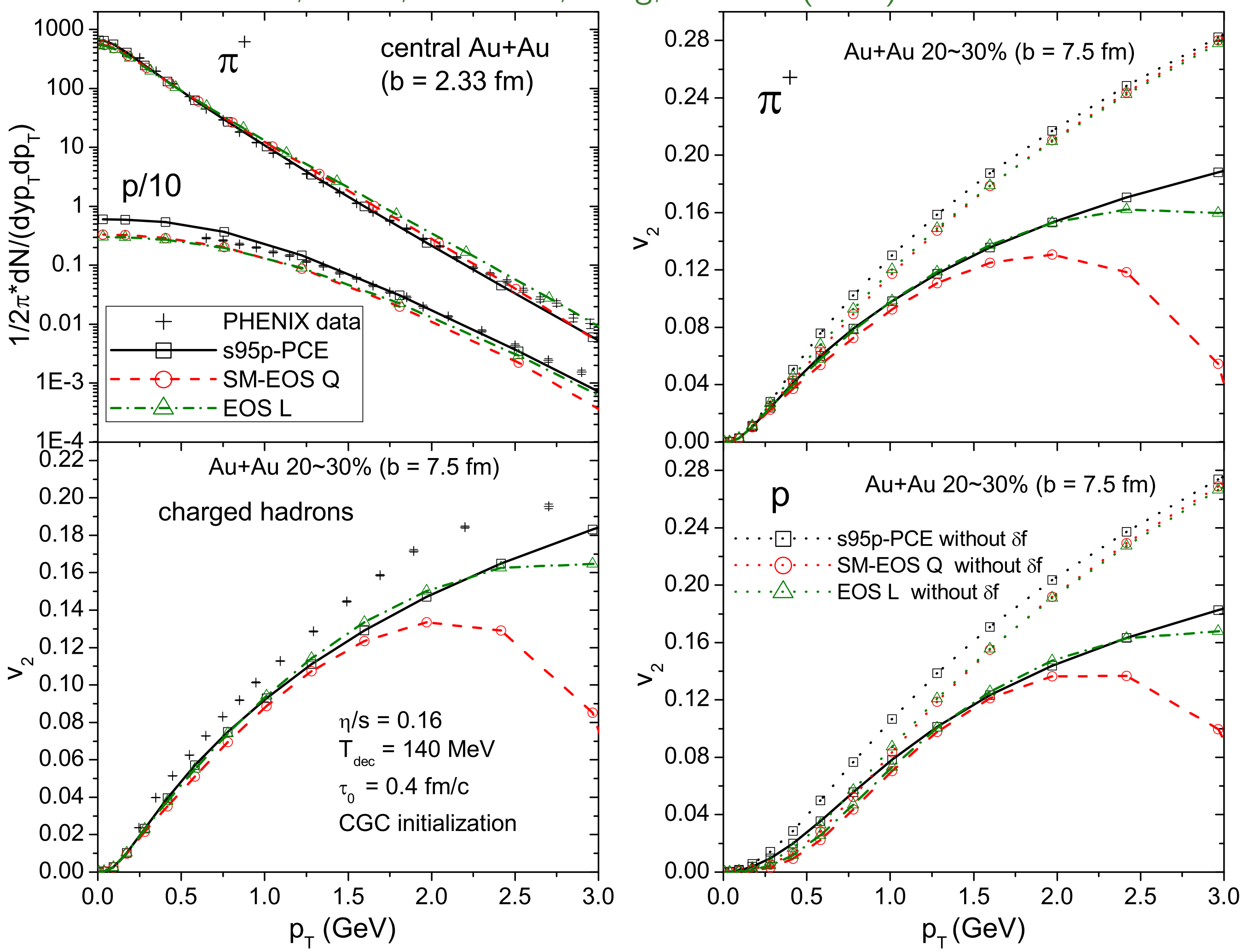


Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy

Smooth transition leads to smaller δf at freeze-out

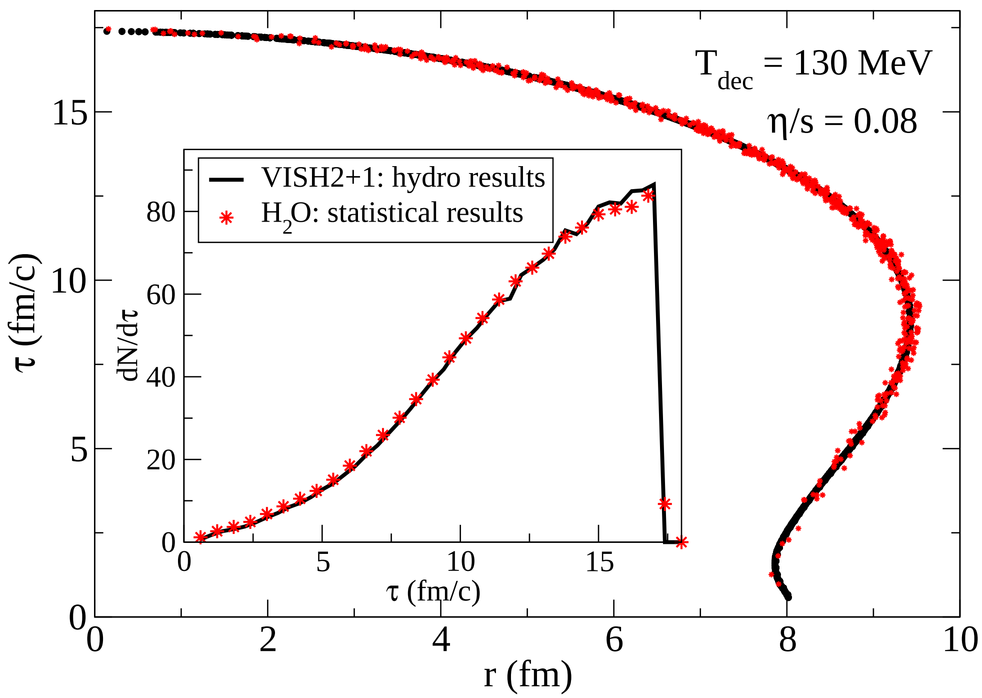
$\Longrightarrow$ larger v_2

H_2O: Hydro-to-OSCAR converter

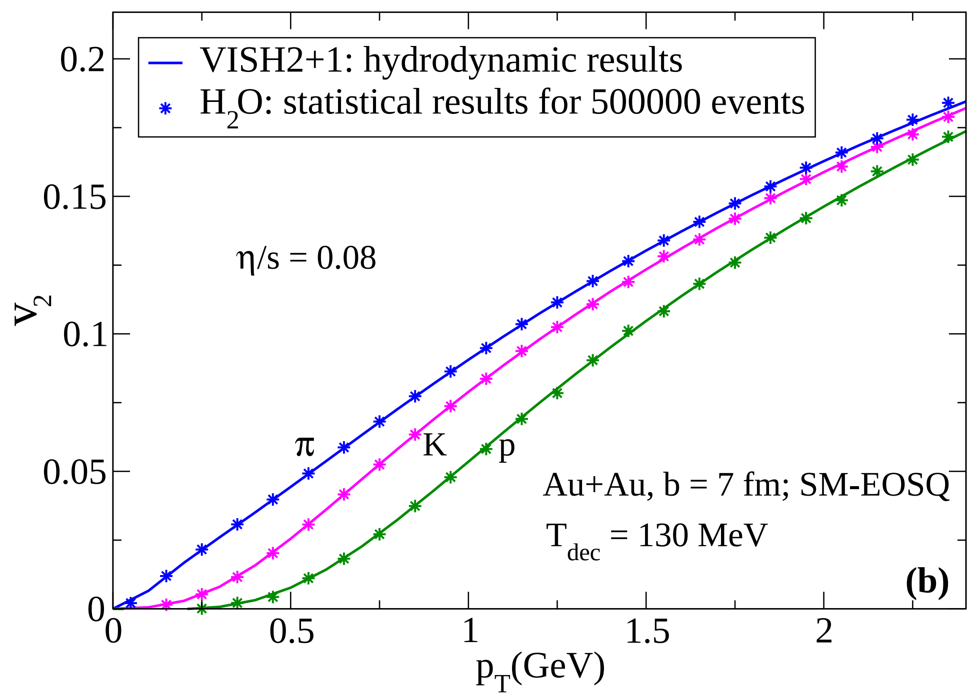
Monte-Carlo interface that samples hydrodynamic Cooper-Frye spectra (including viscous correction δf) on conversion surface to generate particles at positions x_i^μ with momenta p_i^μ for subsequent propagation in `UrQMD` (or any other OSCAR-compatible hadron cascade afterburner)

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 0$



200 A GeV Au+Au, $b = 7$ fm



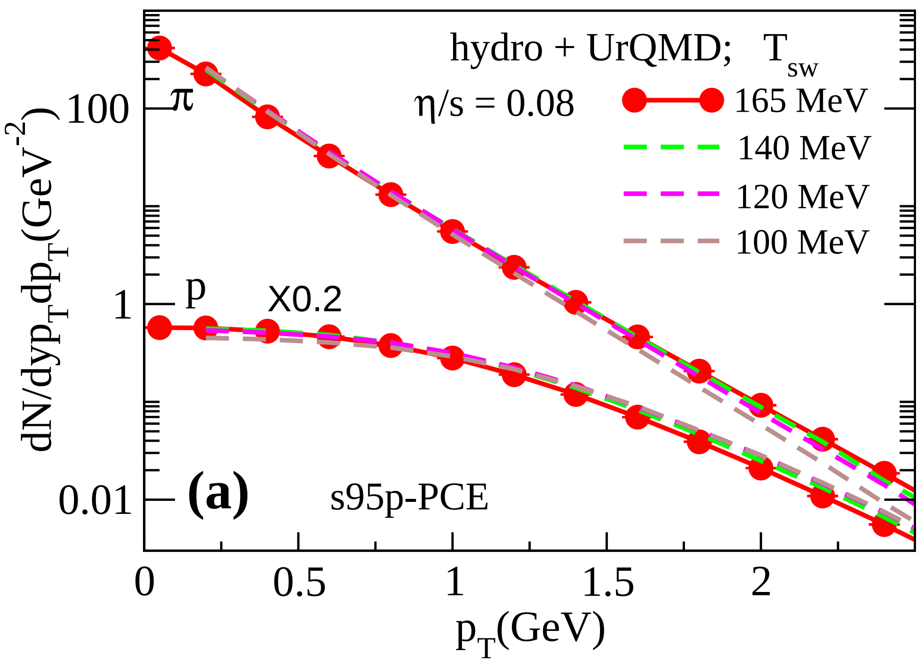
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to T_{sw} (Teaney, 2000):

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



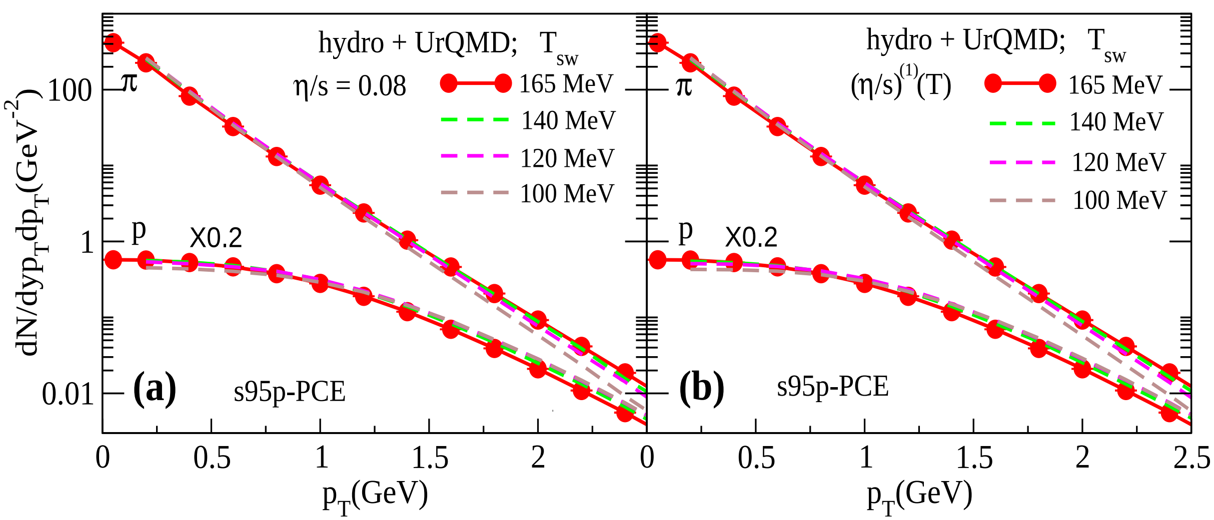
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to $T_{\rm sw}$ **but v_2 does:**

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



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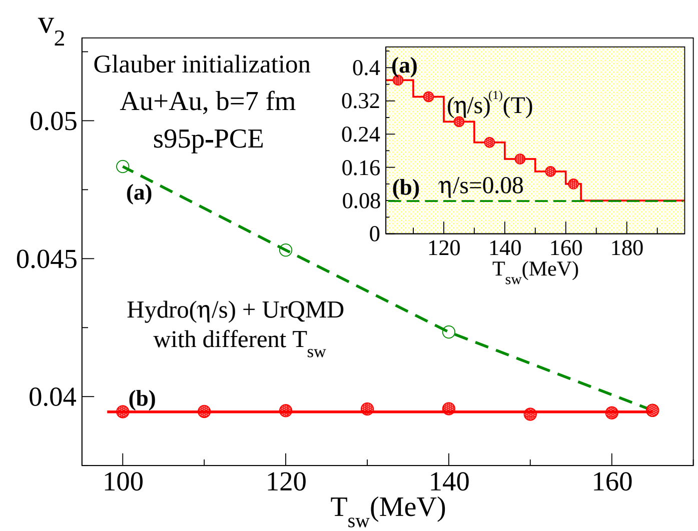


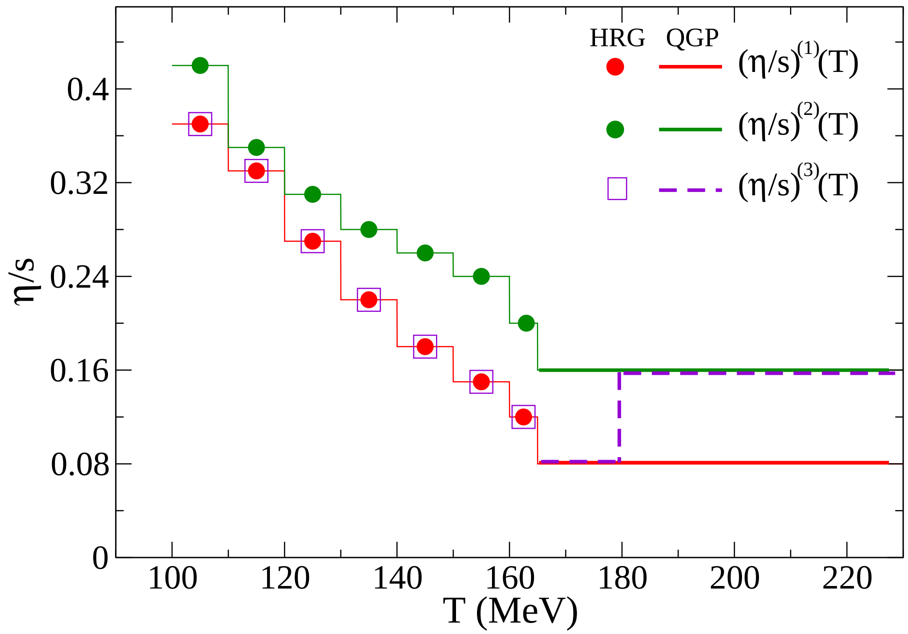
Viscous hydro with fixed $\eta/s = 0.08$ generates more v_2 below T_c than does UrQMD
$\Longrightarrow$ UrQMD is more dissipative

VISH2+1 simulation of UrQMD dynamics requires T-dependent $(\eta/s)(T)$ that increases towards lower temperature

Is there a switching window in which UrQMD can be simulated by viscous hydro?

Unfortunately NO!

Song, Bass, Heinz, PRC 83 (2011) 2011



$(\eta/s)(T)$ extracted by trying to reproduce v_2 independent of switching temperature depends on δ_f input into UrQMD from hadronizing QGP

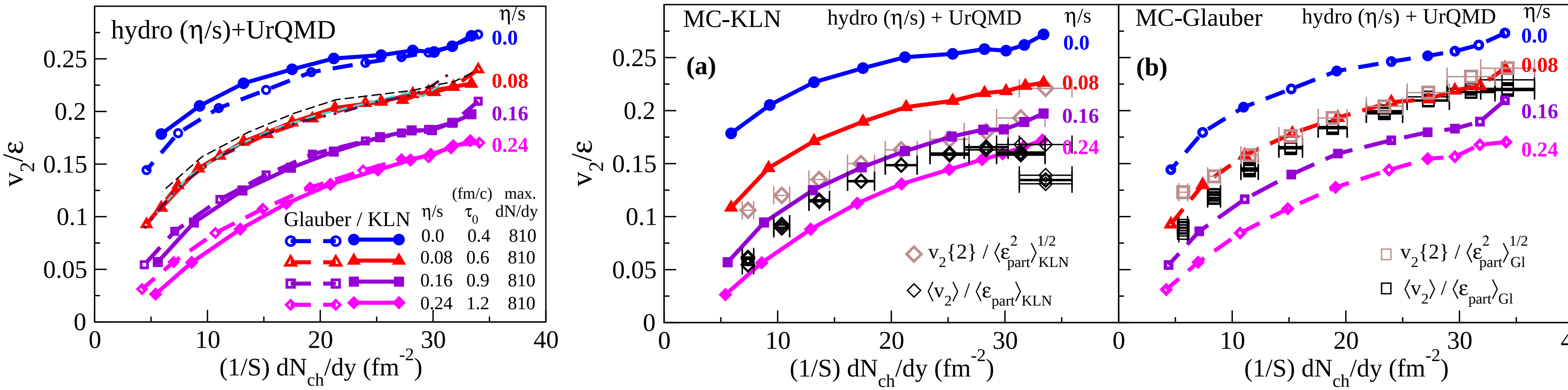
$\Longrightarrow$ δf relaxes too slowly in UrQMD to be describable by viscous Israel-Stewart hydro

$\Longrightarrow$ extracted $(\eta/s)(T)$ not a proper UrQMD transport coefficient

$\Longrightarrow$ **UrQMD dynamics can't be described by viscous Israel-Stewart hydrodynamics**

Extraction of $(\eta/s)_{\rm QGP}$ from AuAu@RHIC

H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301

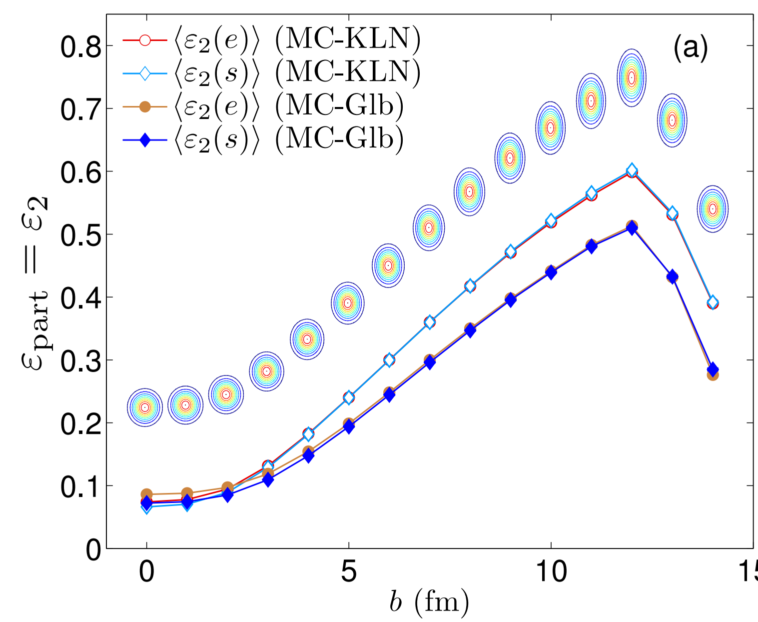


$$\mathbf{1 < 4\pi(\eta/s)_{\rm QGP} < 2.5}$$

- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\rm ch}/\varepsilon_x$ vs. $(1/S)(dN_{\rm ch}/dy)$ is "universal", i.e. depends **only on** $\boldsymbol{\eta/s}$ but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty: $\varepsilon_x^{\rm Gl}$ vs. $\varepsilon_x^{\rm KLN}$ $\longrightarrow$
- smaller effects: *early flow* $\to$ increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % $\to$ larger η/s

  bulk viscosity $\to$ affects $v_2^{\rm ch}(p_T)$, but $\approx$ not $v_2^{\rm ch}$

Zhi Qiu, U. Heinz, arXiv:1104.0650



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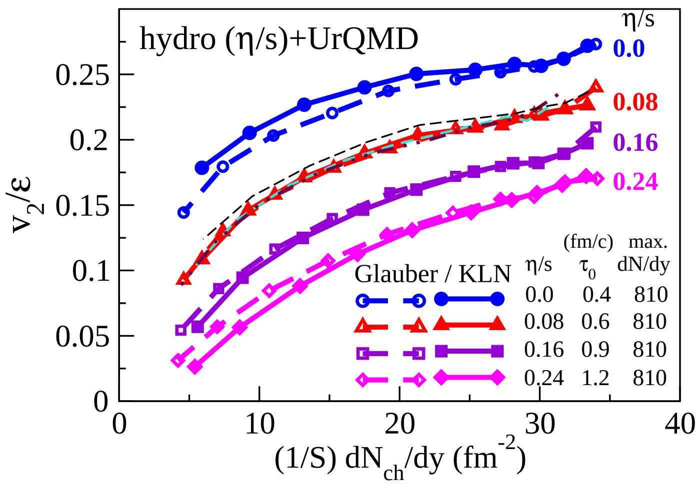

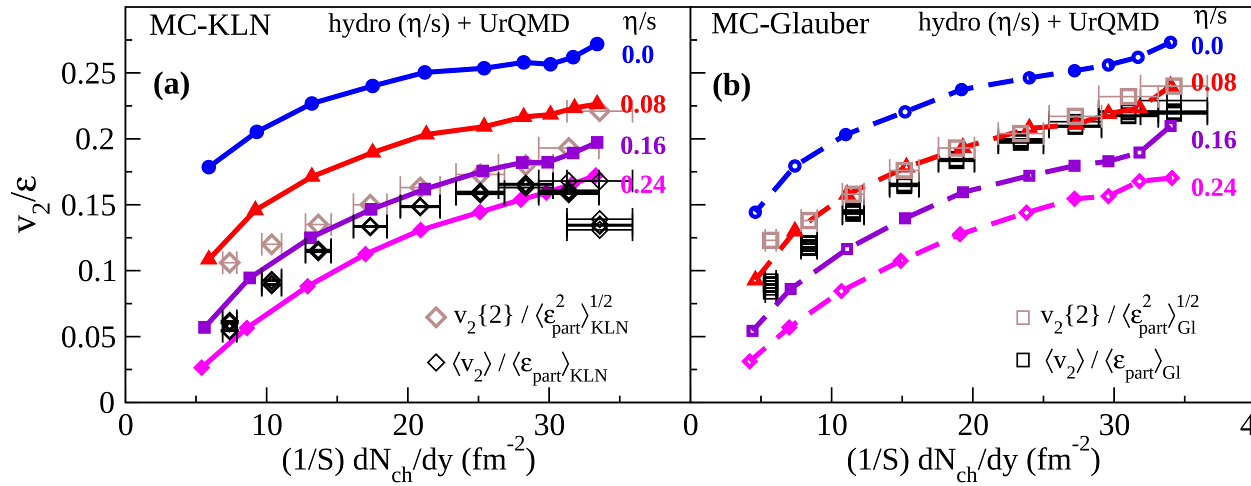

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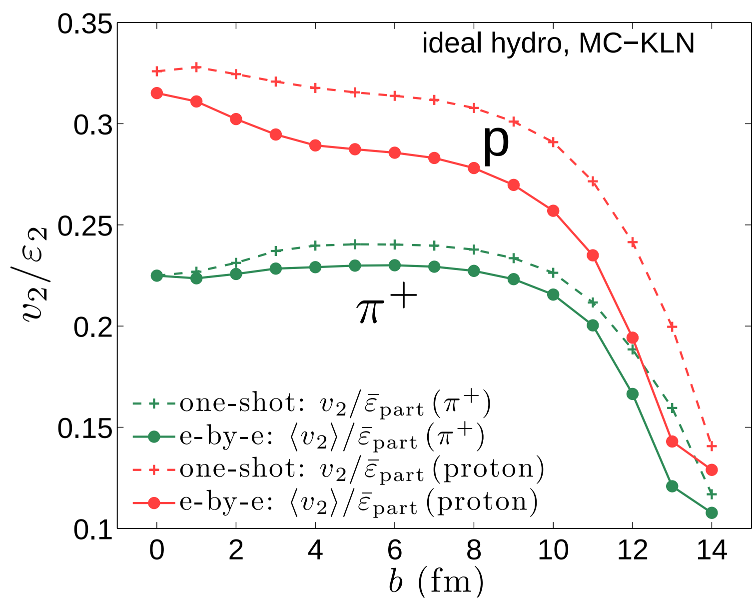
- dominant source of uncertainty: $\varepsilon_x^{\rm Gl}$ vs. $\varepsilon_x^{\rm KLN}$
- smaller effects: *early flow* $\longrightarrow$ increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % $\longrightarrow$ larger η/s

  bulk viscosity $\longrightarrow$ affects $v_2^{\rm ch}(p_T)$, but $\approx$ not $v_2^{\rm ch}$

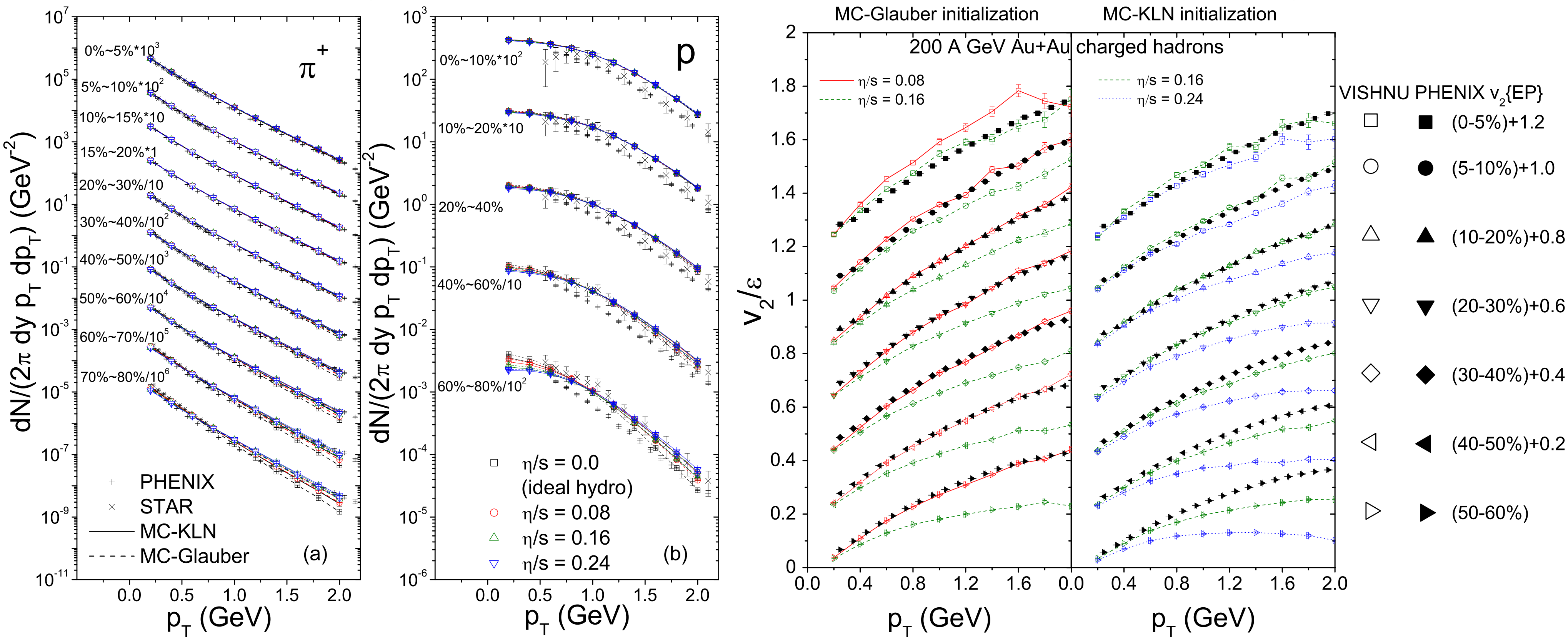
  e-by-e hydro $\longrightarrow$ decreases $\frac{v_2^{\rm ch}}{\varepsilon}$ by $\lesssim 5\%$ $\longrightarrow$ smaller η/s

Zhi Qiu, U, Heinz, arXiv:1104.0650



Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

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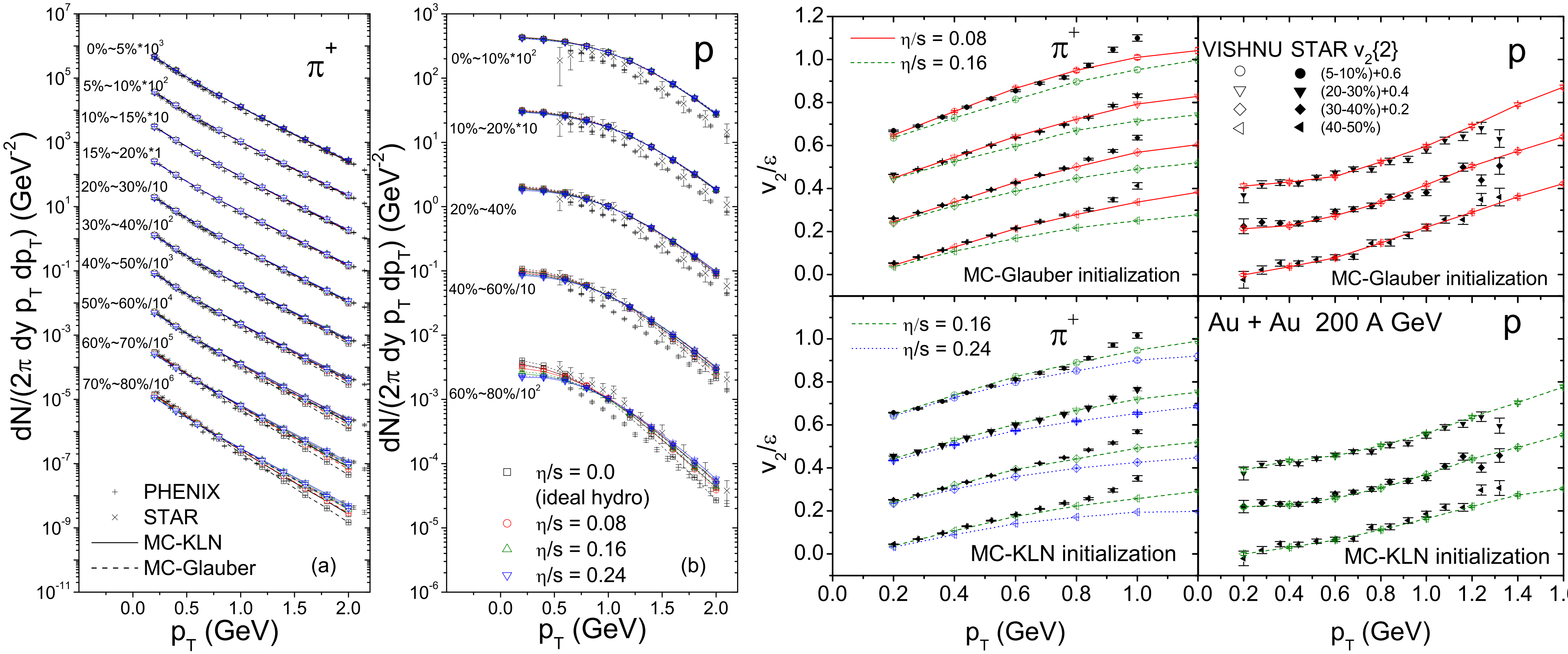
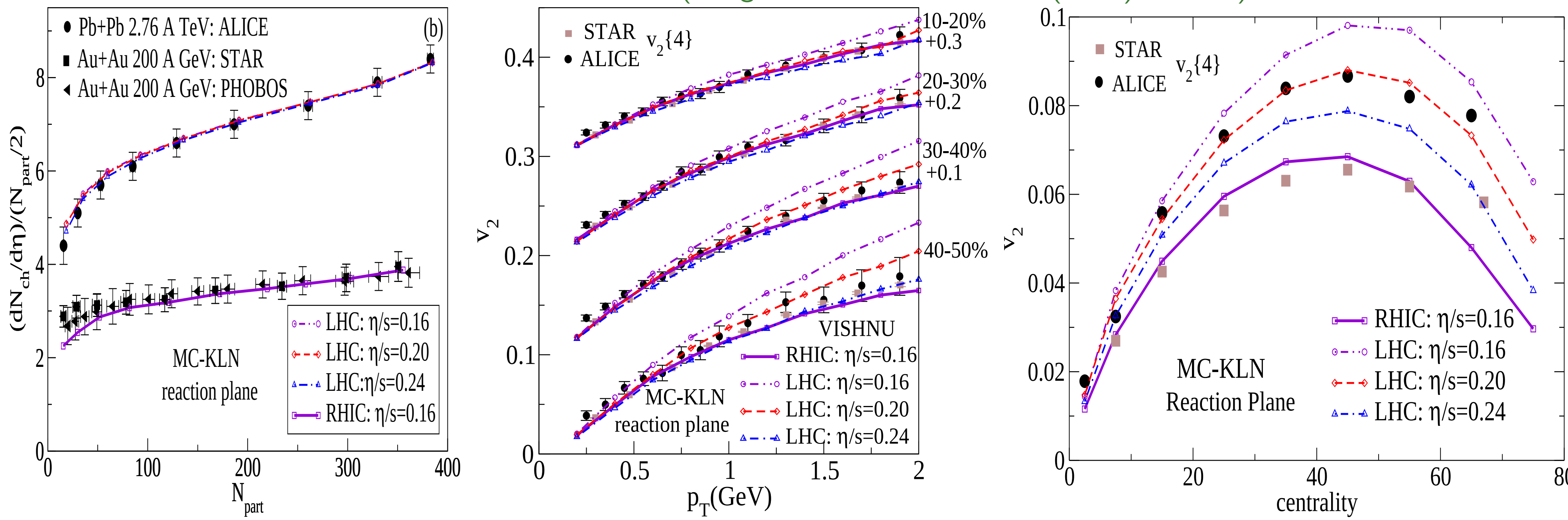


- $(\eta/s)_{\mathrm{QGP}} = 0.08$ for MC-Glauber and $(\eta/s)_{\mathrm{QGP}} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
- A purely hydrodynamic model (without UrQMD afterburner) with the same values of η/s does almost as well (except for centrality dependence of proton $v_2(p_T)$)
- Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ($\tau_0 = 0.6$ instead of 0.9 fm/c), otherwise proton spectra are too steep
- These η/s values agree with Luzum & Romatschke, PRC78 (2008), even though they used EOS with incorrect hadronic chemical composition $\Longrightarrow$ shows robustness of extracting η/s from total charged hadron v_2

Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (Song, Bass, Heinz, PRC 83 (2011) 054912)



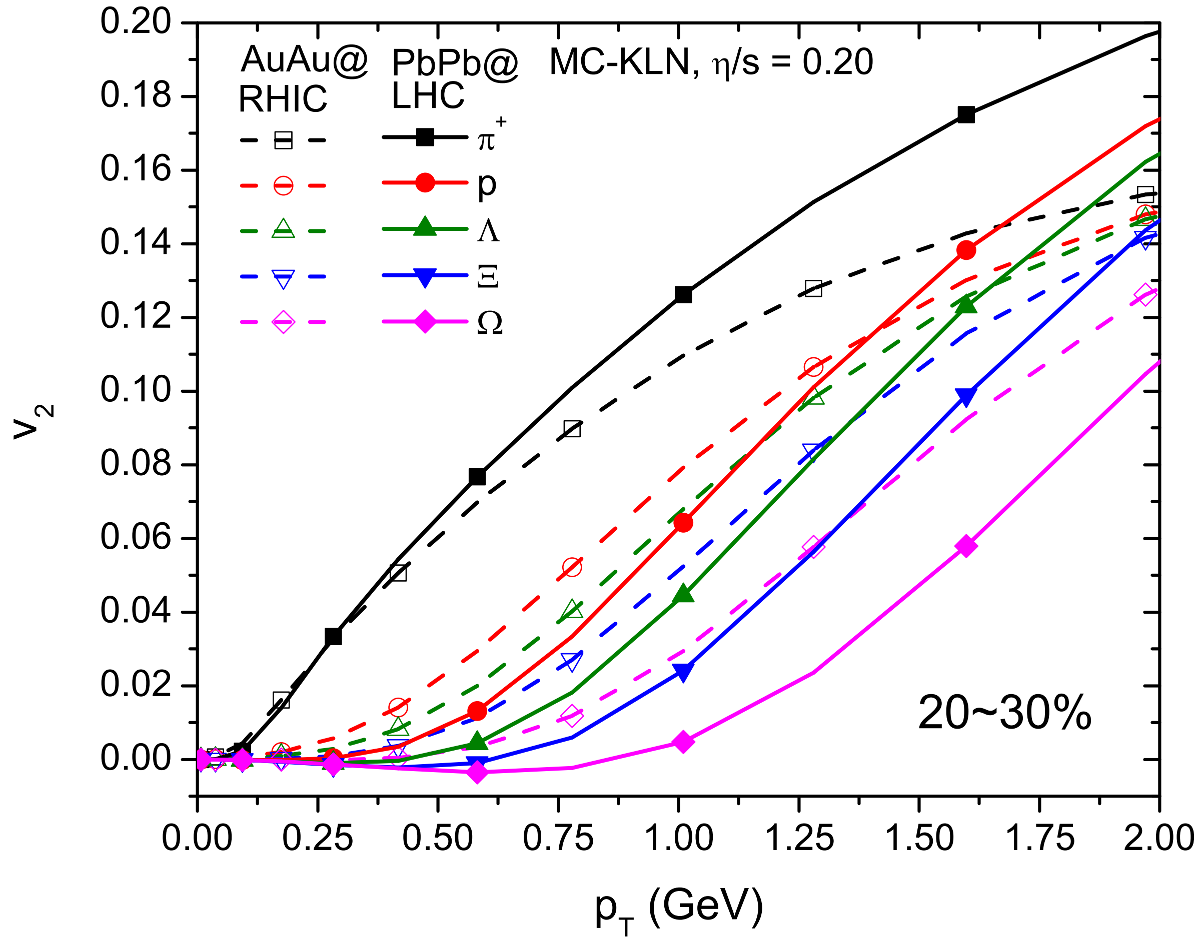
- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ and integrated v_2 in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro $\Longrightarrow$ Shen et al., arXiv:1105.3226
- **but:** At LHC, we see significant sensitivity of v_2 to initialization of viscous pressure tensor $\pi^{\mu\nu}$ (Navier-Stokes or zero), and it is not excluded that it may be possible to bring down v_2 at LHC to the ALICE data without increasing η/s at higher T (requires more study)

  $\Longrightarrow$ **QGP at LHC perhaps a bit, but not dramatically more viscous than at RHIC!**

Why is $v_2^{\mathrm{ch}}(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)

C. Shen, U. Heinz, P. Huovinen, H. Song, arXiv:1105.3226



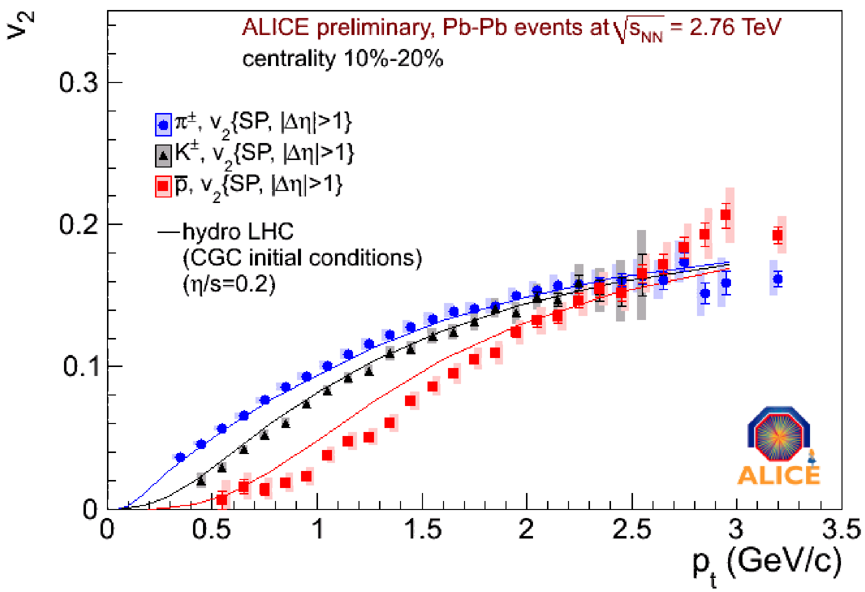
$v_2^{\pi}(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases

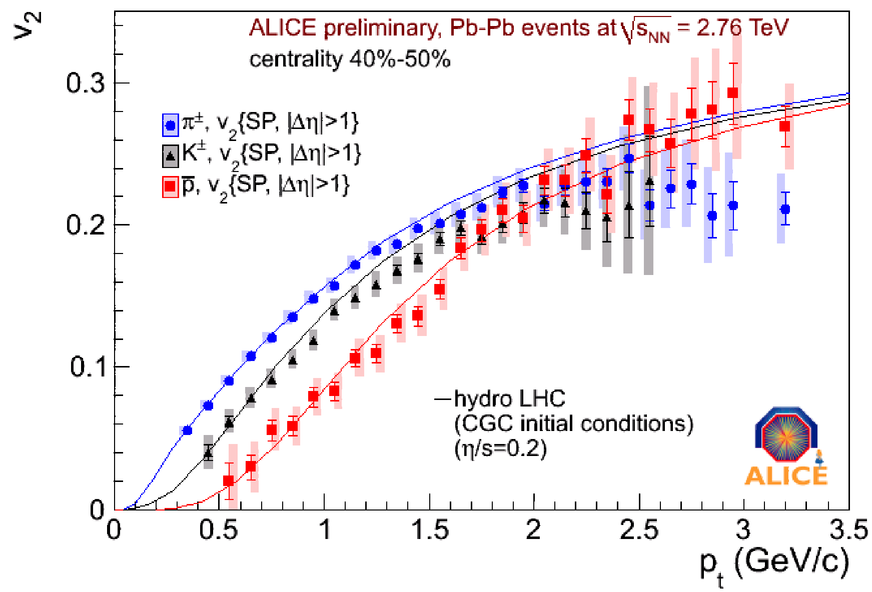
(radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

This is a hard prediction of hydrodynamics! (See also Nagle, Bearden, Zajc, arXiv:1102.0680)

Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE Lines: Shen et al., arXiv:1105.3226 (VISH2+1)

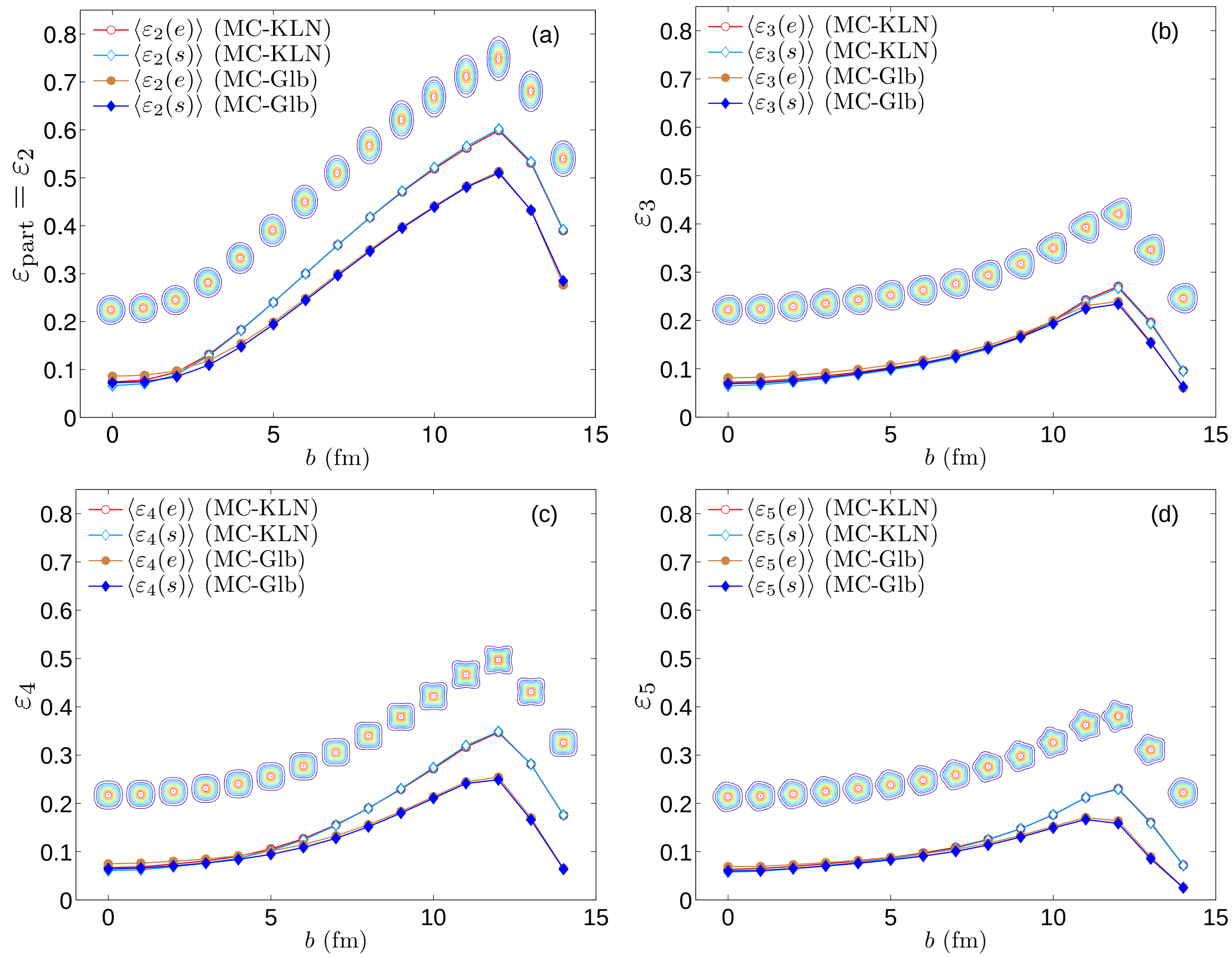




Perfect fit in semi-peripheral collisions, but not enough proton radial flow in central collisions $\Longrightarrow$ hadronic cascade (VISHNU) may help

Back to the elephant in the room: How to eliminate the large model uncertainty in the initial eccentricity?

Zhi Qiu and U. Heinz, arXiv:1104.0650



Initial eccentricities ε_n and angles ψ_n:

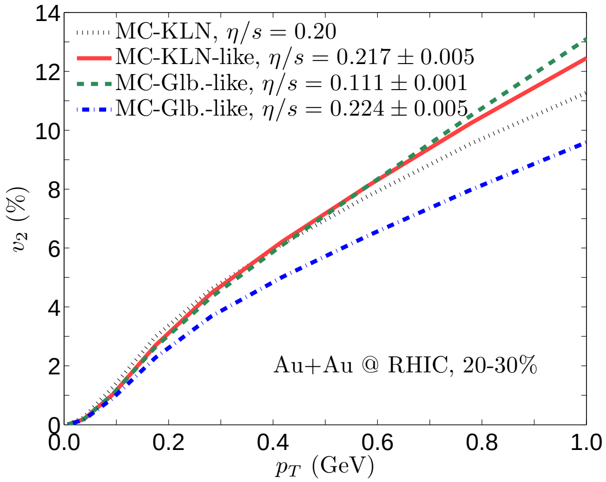
$$\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$$

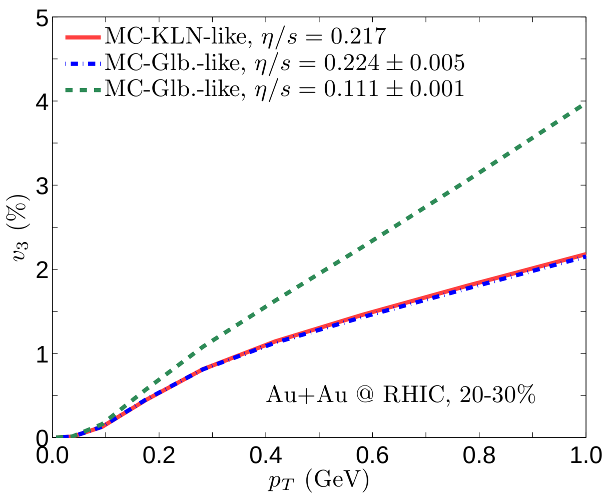
- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber
- Angles of ε_2 and ε_4 are correlated with reaction plane by geometry, whereas those of ε_3 and ε_5 are random (purely fluctuation-driven)
- While v_4 and v_5 have mode-coupling contributions from ε_2, v_3 is almost pure response to ε_3 and $v_3/\varepsilon_3 \approx$ const. over a wide range of centralities (for details see arXiv:1104.0650)

$\Longrightarrow$ **Idea:** Use total charged hadron $v_3^{\rm ch}$ to determine $(\eta/s)_{\rm QGP}$, then check $v_2^{\rm ch}$ to distinguish between MC-KLN and MC-Glauber!

Shooting the elephant

Zhi Qiu and U. Heinz, to be published





Proof of principle calculation:

- Take ensemble of sum of deformed Gaussian profiles, $s(\boldsymbol{r}_\perp) = s_2(\boldsymbol{r}_\perp; \tilde{\varepsilon}_2, \psi_2) + s_3(\boldsymbol{r}_\perp; \tilde{\varepsilon}_3, \psi_3)$, with
  1. equal Gaussian radii $R_2^2 = R_3^2 = 8\,\mathrm{fm}^2$ to reproduce $\langle r_\perp^2 \rangle$ of MC-KLN source for 20-30% AuAu
  2. $\tilde{\varepsilon}_2$ and $\tilde{\varepsilon}_3$ adjusted such that
     - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\mathrm{KLN}}^{20-30\%}$ ("MC-KLN-like")
     - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\mathrm{Gl}}^{20-30\%}$ ("MC-Glauber-like")
  3. $\psi_2 = 0$, ψ_3 (direction of triangularity) distributed randomly
- Use $v_2^\pi(p_T)$ from VISH2+1 for $\eta/s = 0.20$ with MC-KLN initial conditions for 20-30% AuAu as "mock data"
- Fit mock $v_2^\pi(p_T)$ data with VISH2+1 for "MC-Glauber-like" or "MC-KLN-like" Gaussian initial conditions with both elliptic and triangular deformations by adjusting η/s
  $\Longrightarrow$ $(\eta/s)_{\mathrm{KLN}} = 0.217 \pm 0.005$ for "MC-KLN-like",
  $(\eta/s)_{\mathrm{Gl}} = 0.111 \pm 0.001$ for "MC-Glauber-like"
- Compute $v_3^\pi(p_T)$ for "MC-KLN-like" fit with $(\eta/s)_{\mathrm{Gl}}$=0.217 and reproduce it with "MC-Glauber-like" initial condition by readjusting η/s
  $\Longrightarrow$ $(\eta/s)_{\mathrm{Gl}}^{v3} = 0.224 \pm 0.005$ for "MC-Glauber-like"
- Compute $v_2^\pi(p_T)$ for "MC-Glauber-like" initial profiles with readjusted $(\eta/s)_{\mathrm{Gl}}^{v3} = 0.224$ and compare with "MC-Glauber-like" fit to original mock data $\Longrightarrow$ clearly visible (and measurable) difference!

This exercise proves: (i) Fitting $v_3(p_T)$ data with MC-Glauber and MC-KLN initial conditions yields the same η/s (within narrow error band); (ii) The corresponding $v_2(p_T)$ fits are quite different, and only one (more precisely: at most one!) of the models will fit the corresponding $v_2(p_T)$ data.

Conclusions

- Hybrid codes (e.g. VISHNU) that couple viscous hydro evolution of QGP to microscopic hadron cascade now allow a determination of $(\eta/s)_{\rm QGP}$ with $\mathcal{O}(25\%)$ precision **if the initial fireball eccentricity is known to better than 5% relative accuracy**

- With VISHNU good global fits that describe all single-particle observables for soft hadron production (spectra, elliptic flow) at all but the most peripheral AuAu collision centralities are obtained, for both MC-Glauber and MC-KLN initial conditions, by using $(\eta/s)_{\rm QGP}=0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP}=0.16{-}0.20$ for MC-Glauber

- Event-by-event hydrodynamics with fluctuating initial conditions yields somewhat less v_2/ε_2 than single-shot hydro with smooth average initial profiles $\Longrightarrow$ this will bring $(\eta/s)_{\rm QGP}$ from charged hadrons down by $\sim 0.02-0.03$. For proton v_2, event-by-event hydro matters a lot.

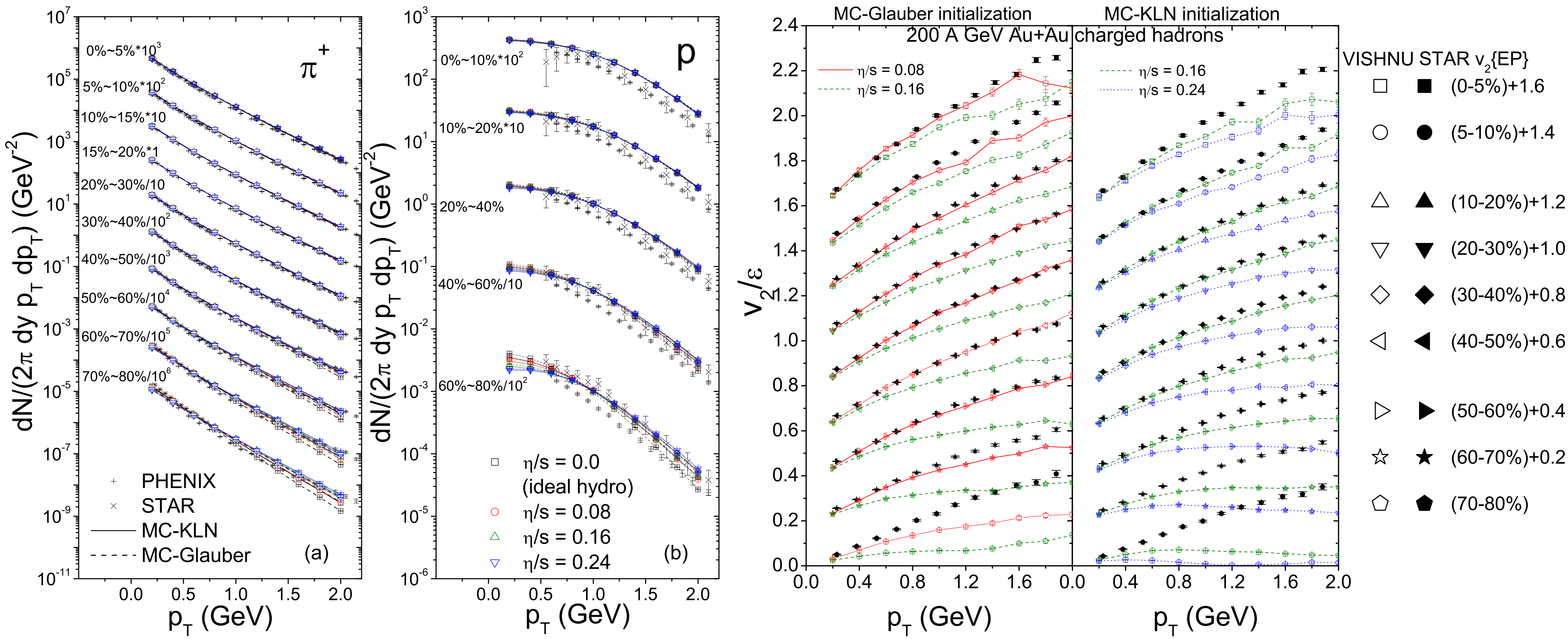
- While MC-Glauber and MC-KLN give ε_2 that differ by 20-25%, they give almost identical ε_3 (which is not geometric but fluctuatiuon-driven). Only one of them will be able to fit simultaneously both v_2 and v_3.

- This may be enable us to gain the necessary control over initial conditions to make a precise (i.e. better than factor 2) measurement of $(\eta/s)_{\rm QGP}$.

Supplements

Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



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Panel Discussion

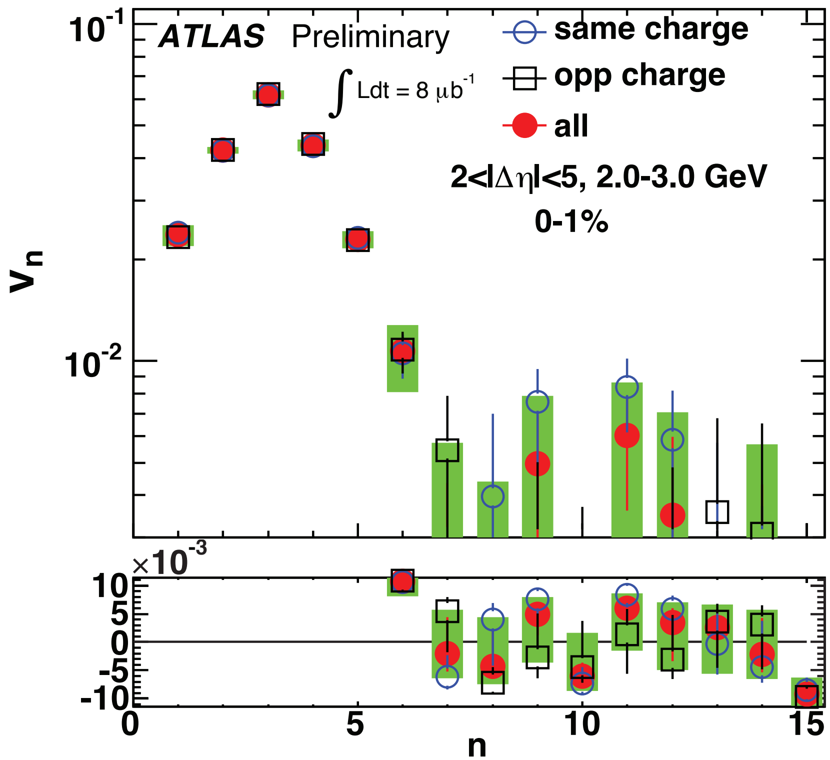
RHIC data have led to a series of paradigmatic shifts in our understanding of the Little Bang:

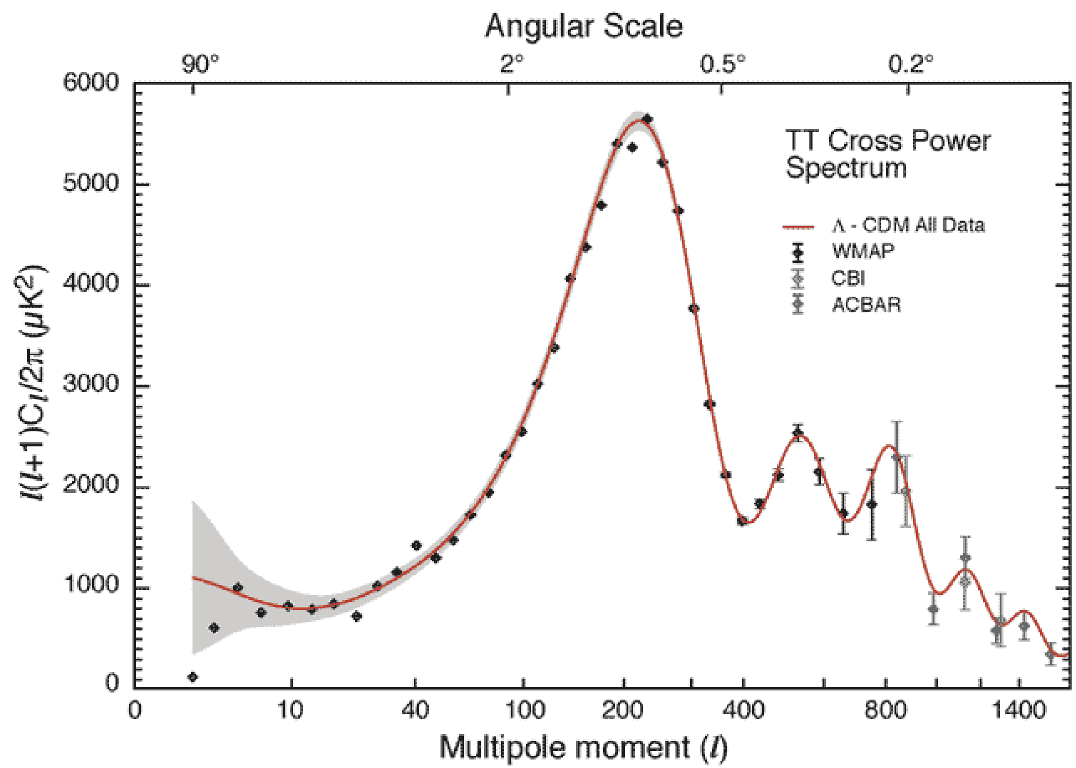
2002-2003 The **QGP** is **not** a weakly coupled quark-gluon gas **but** a strongly coupled, almost "perfect" liquid

2003-2008 Deviations from local equilibrium **(dissipative effects)** play an essential role and dictate much of the phenomenology
Easier to measure transport coefficients (e.g. η/s, $\hat{q}$, charm drag and diffusion) by varying $\sqrt{s}$, A, b, ϕ than thermodynamic properties of the QGP (e.g. EOS, c_s, μ_{D})
Differences in transport properties of QGP and HRG more important than differences in thermodynamic variables (P, e, s, n_B)

2009-2010 **"COBE revolution":** Many key experimental phenomena cannot be described by classical evolution of smooth mean field configurations; quantum **fluctuations** in the initial state play an essential role in any quantitative understanding of RHIC data

The fluctuation "power spectrum" of the Little Bang (Mocsy & Sorensen)





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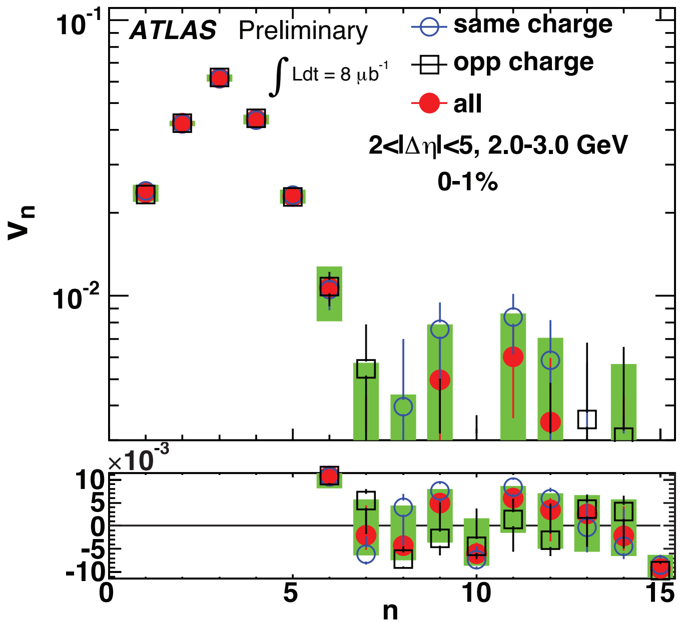

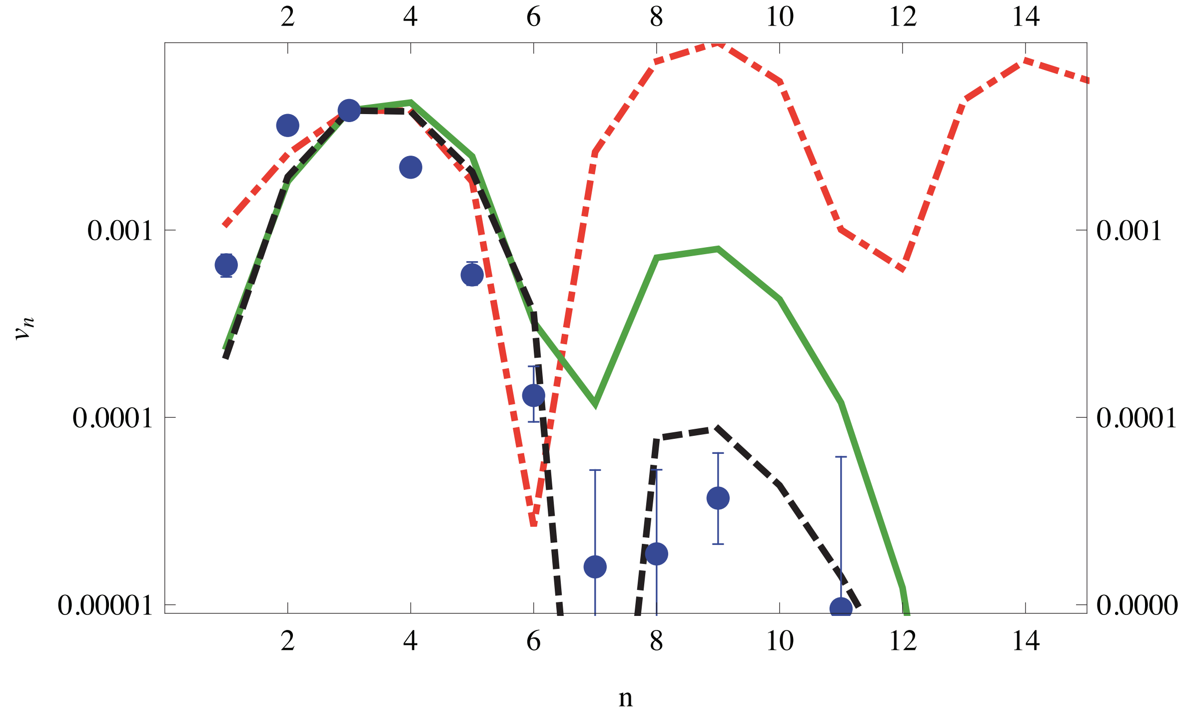

- Relating the measured "anisotropic flow power spectrum" (i.e. v_n vs. n) to the "initial fluctuation power spectrum" (i.e. ε_n vs. n) provides access to the QGP transport coefficients (likely not only η/s, but also ζ/s, τ_π, τ_Π ...)
- Power spectrum of initial fluctuations (in particular its $\sqrt{s}$ dependence) can (probably) be calculated from first principles via CGC effective theory (Dusling, Gelis, Venugopalan, arXiv:1106.3927)
- Collisions between different species, at different collision centralities, and at different $\sqrt{s}$ create Little Bangs with characteristically different power spectra

A comment

(Viscous) hydro works better at higher (RHIC 200, LHC) than at lower energies (RHIC BES, SPS/AGS)

$\Longrightarrow$ breakdown of macroscopic approach at low energies ($v_2^{\pi^+} \neq v_2^{\pi^-}$, $v_2^p \neq v_2^{\bar{p}}$) may prove fatal to our attempts to measure the thermodynamic properties of QCD matter near or below T_c. (This does not invalidate the "sweet spot" argument that RHIC is the only machine that allows us to move easily in and out of the region of deconfinement; I am just saying that it will probably not be possible to understand this transition region primarily in terms of the change of thermodynamic characteristics of the matter, but rather in terms of its changing transport properties, caused by a change in degrees of freedom.)

$\Longrightarrow$ limits and breakdown of the hydrodynamic approach require careful exploration at RHIC

Some personal convictions

- To sort out the transport coefficients of the bulk medium and related to hard probes (parton energy loss, heavy quark diffusion, . . .)
$\Longrightarrow$ need systematic studies of $\sqrt{s}$, $A{+}B$, b, and ϕ dependences
This requires a dedicated program and extensive running time

- To obtain access to T-dependence of transport coefficients
$\Longrightarrow$ need large range of $\sqrt{s}$ from low-energy RHIC to top LHC energies (and it will still be difficult)

- To sort out parton energy loss mechanism and parton$\rightarrow$medium backreaction, neither RHIC nor LHC alone will be sufficient

- To perform JET of QGP at all length scales, need large range of Q^2
  Large Q^2 only at LHC
  Lower Q^2 cleaner at RHIC

- We will only find the correct theory of thermalization after having carefully mapped thermalization times phenomenologically, by analyzing systematic studies of flow patterns in $A{+}B$ data at both RHIC and LHC

Looking into the future > 2018

Question: How would the world-wide heavy-ion program > 2018 look without an active RHIC $A{+}B$ program?

Answer: Like RHIC 2005-2010, without active SPS and LHC HI programs

Example: The parton energy loss confusion

It is not hard to predict that the LHC will discover hard probe phenomena at high p_T that will find several competing explanations which differ at low p_T where it will be difficult to test them at the LHC, due to large backgrounds from the fluctuating bulk medium. Will need RHIC data to resolve these ambiguities. I don't believe that that all the necessary data will be taken before 2018, simply because we don't know yet what to look for.

Looking into the future > 2018

By not having a RHIC $A{+}A$ program after 2018, in parallel with the LHC heavy ion and EIC $e{+}A$ programs, we will (at best) delay and (more likely) close the door to a timely and comprehensive understanding of LHC and EIC measurements.

Need coherence, not only with respect to the RHIC $\rightarrow$ EIC transition, but also with respect to the worldwide heavy-ion program (which has strong US involvement in all its different components).

Think about optimizing RHIC detector(s) for complementarity to LHC $A{+}A$ and EIC $e{+}A$ capabilities